BEYOND THE HORIZON:
What is left to learn after *Hubble* about the first billion years?

STEVEN FINKELSTEIN
THE UNIVERSITY OF TEXAS AT AUSTIN

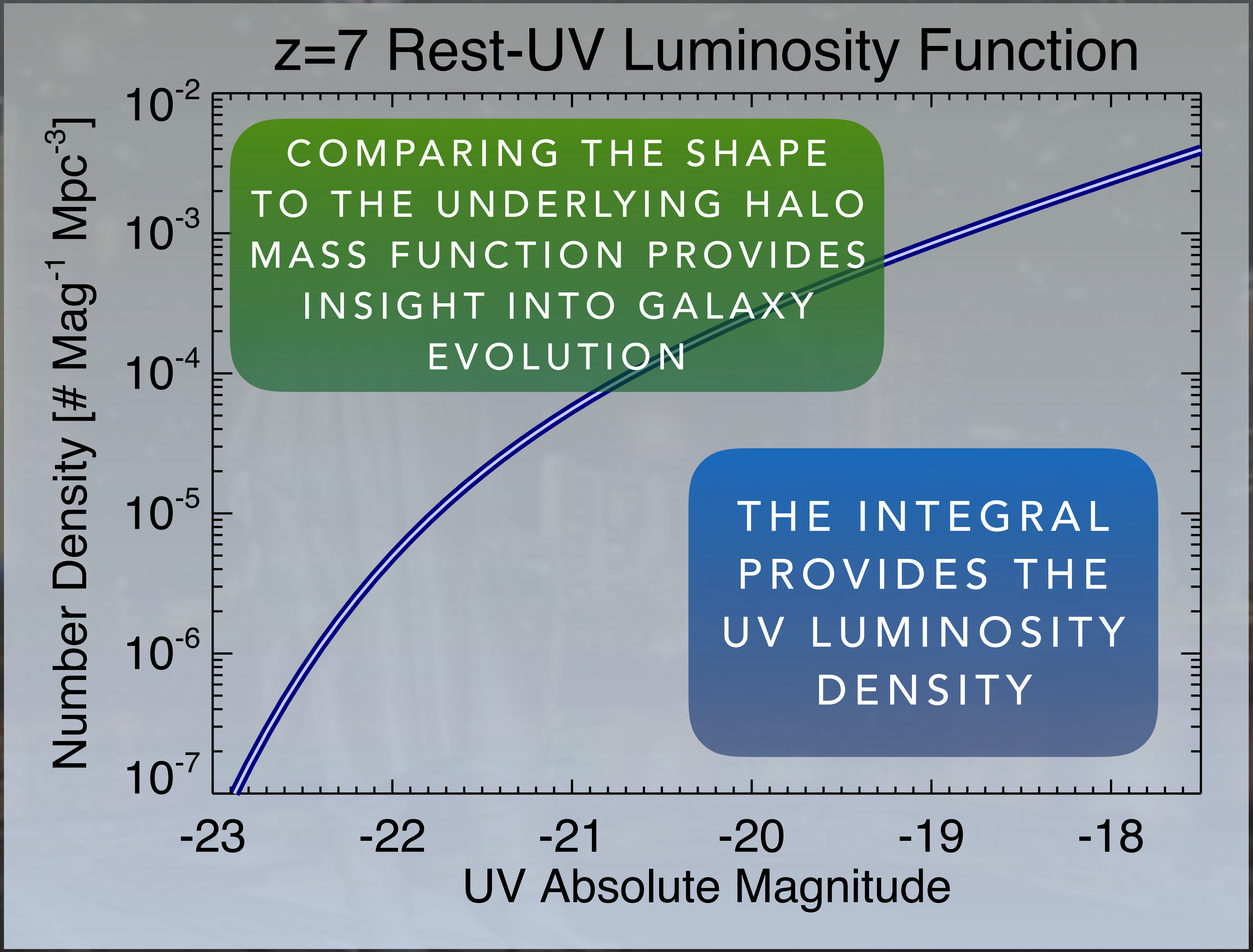
Cosmic Origins Science Interest Group

January 4th, 2016

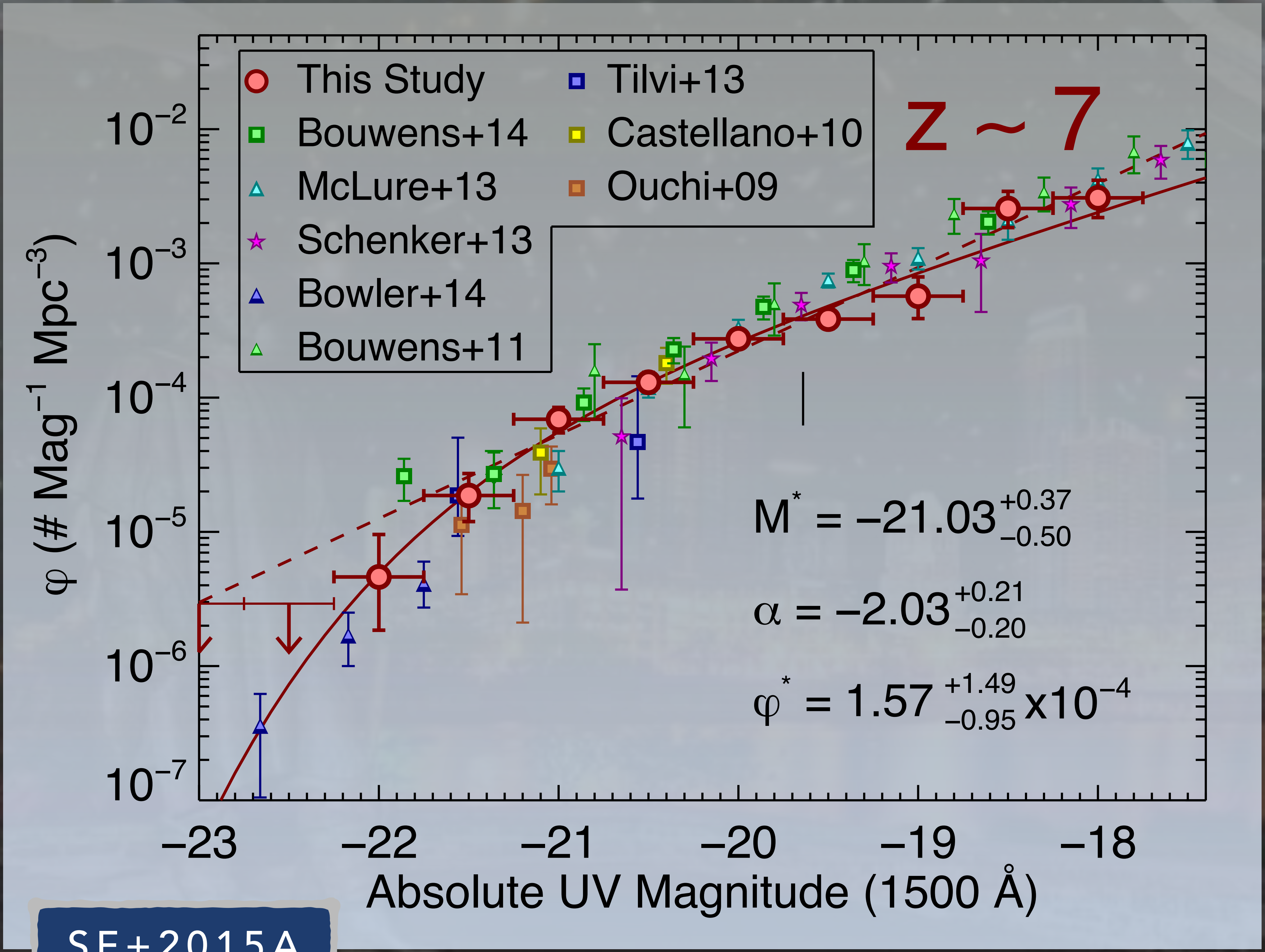
Key remaining question: what are the first galaxies, and when/how did they reionize the universe?

What do we currently know?

OUR PRIMARY GALAXY TOOL: THE UV LUMINOSITY FUNCTION

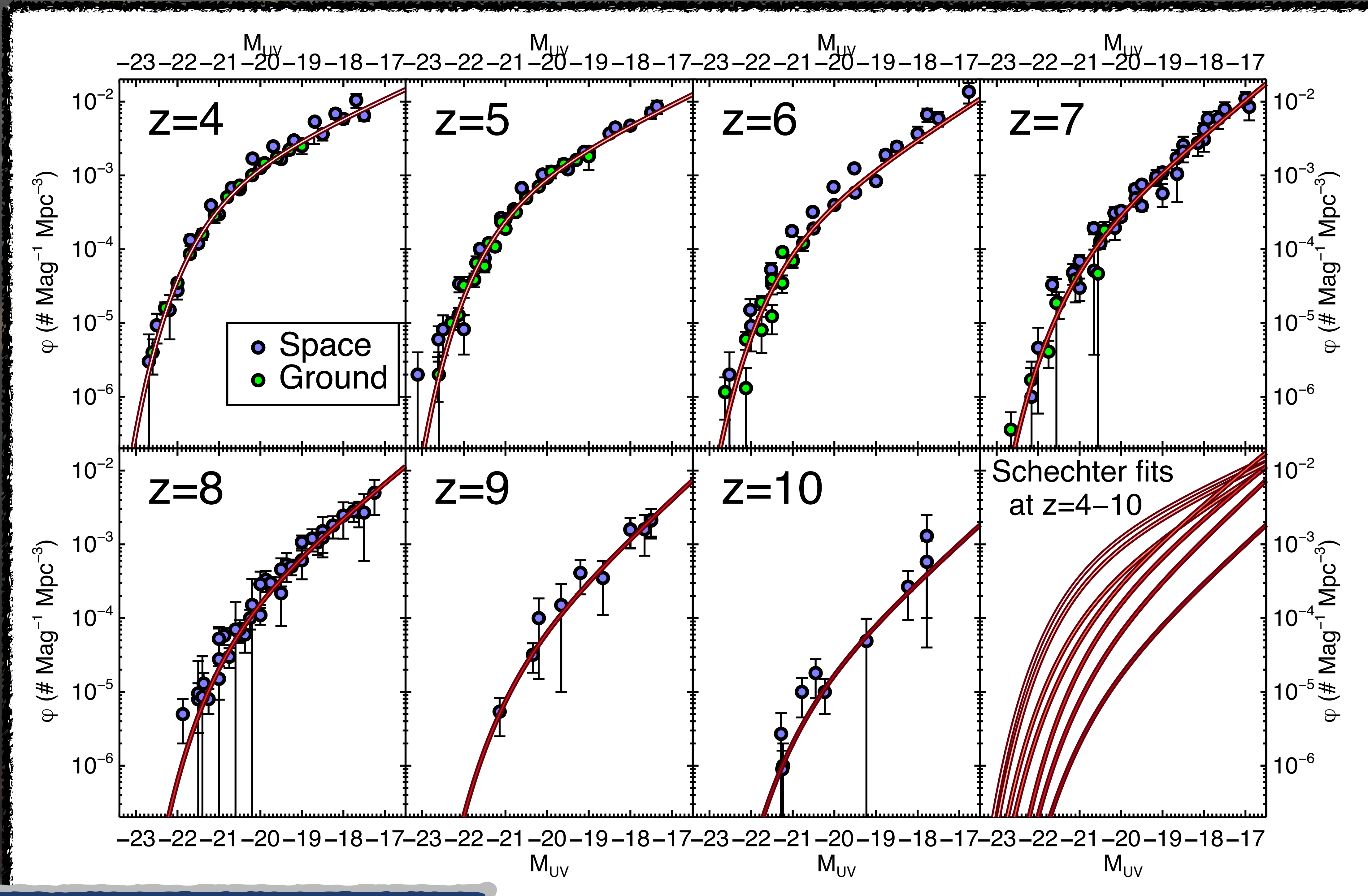


THE CURRENT AGREEMENT AT HIGH REDSHIFT IS VERY GOOD!



SF+2015A

A "CONSENSUS" LUMINOSITY FUNCTION



SF+2015C PASA REVIEW

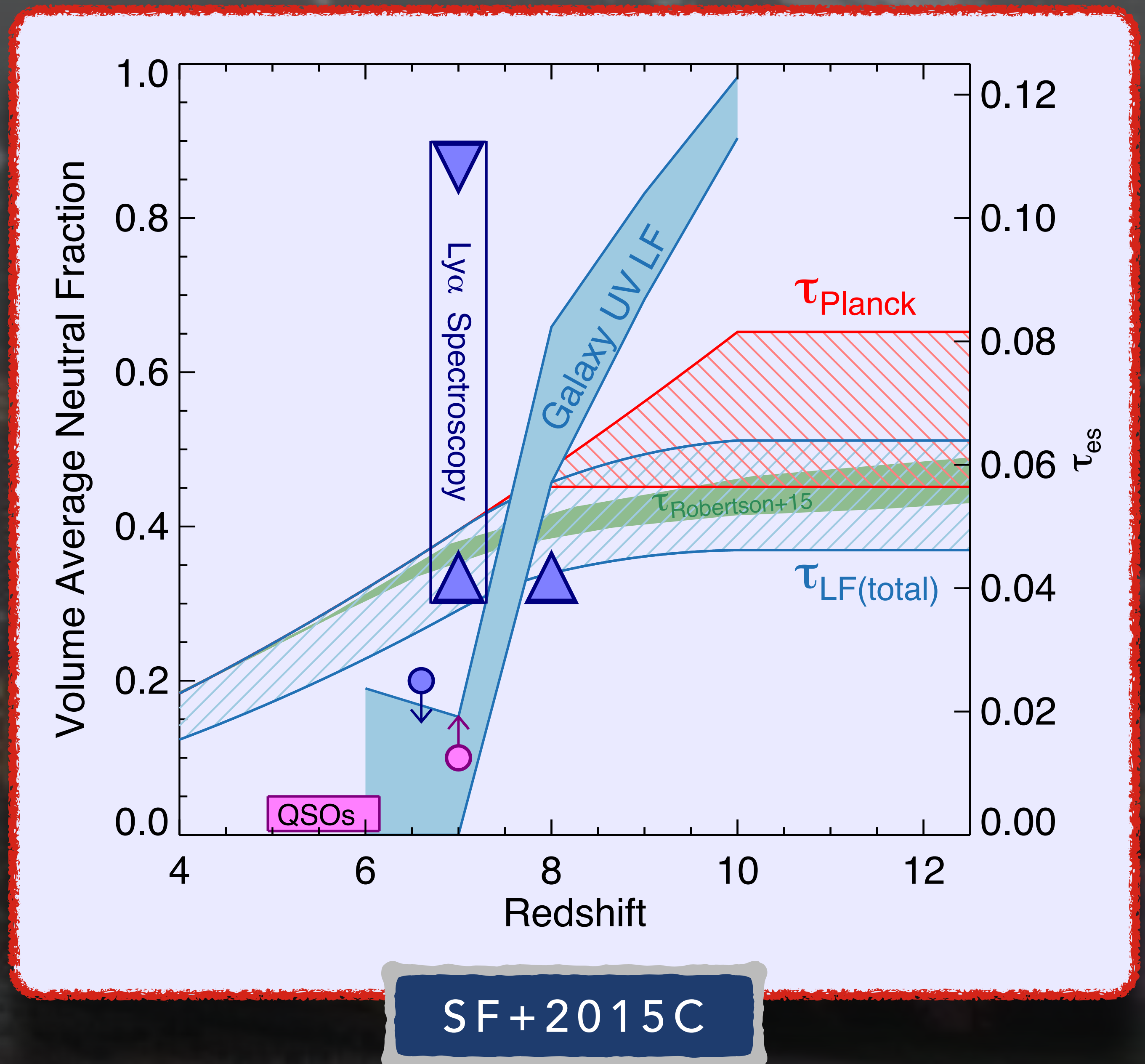
HOW DO WE OBTAIN REIONIZATION CONSTRAINTS FROM THE LUMINOSITY FUNCTION?

- Step 1: Integrate the UV LF to obtain the specific UV luminosity density: ρ_{UV} [erg s^{-1} Hz^{-1} Mpc^{3}]
  - Assumption: Need to assume a minimum value of M_{UV} (especially when α < 2).
    - Common values in the literature: -17, -15, -13, -10
    - We see galaxies down to -17, so its likely fainter. We assume M_{lim}=-13, though this bears watching from the theoretical side (e.g., Jaacks+12, O'Shea+15).
- Step 2: Choose a reionization model.
  - Assumptions: Madau (1999) model, C=3, f_{esc}=13% (upper limit at z=6 from SF+2012b), conversion from ionizing to non-ionizing UV for a Salpeter IMF, and 20% Solar metallicity.

NEEDED IMPROVEMENTS

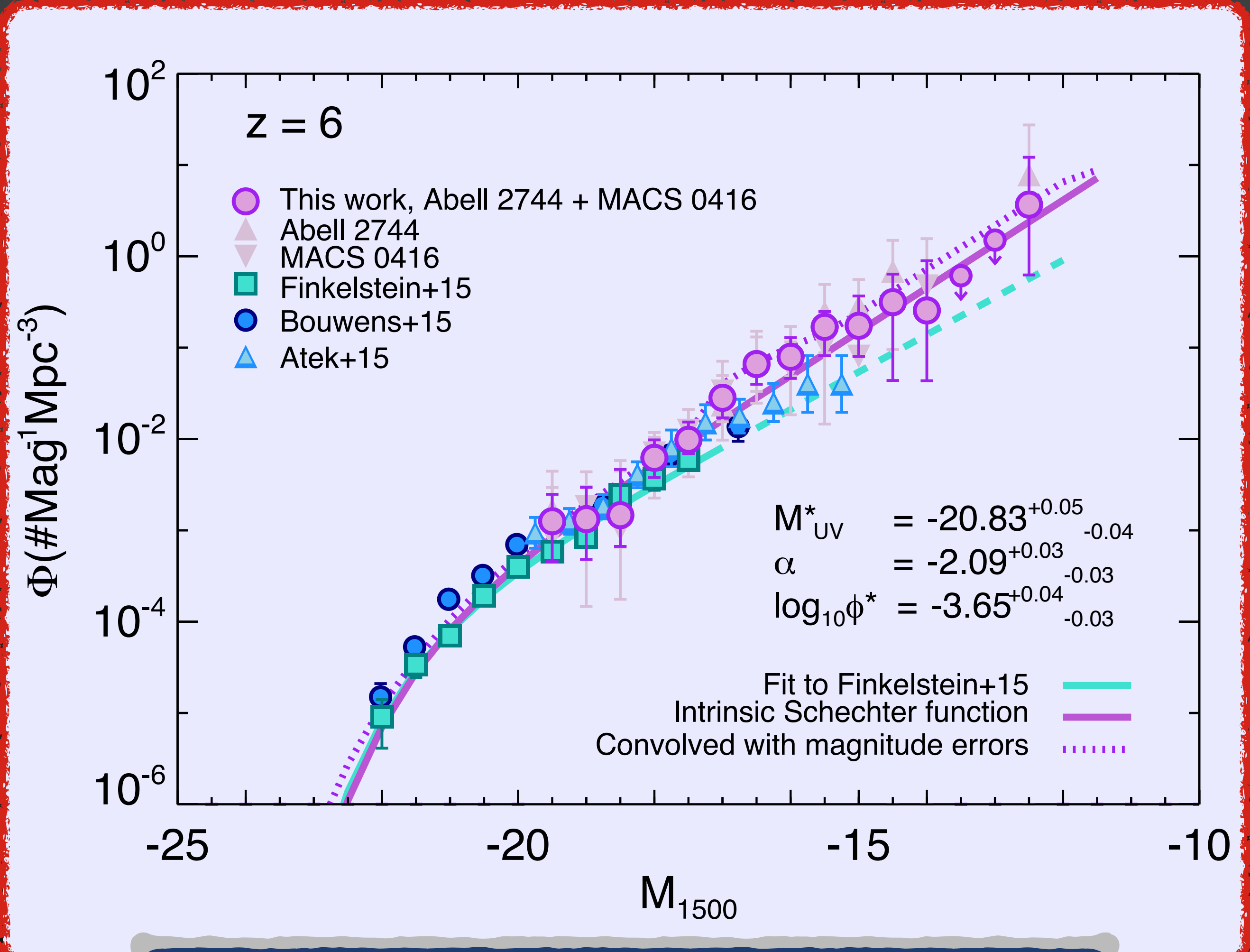
- The consensus LF constraints give a 68% confidence range on the 50% reionization redshift of 7.7 < z < 8.2.

- This is a dramatic improvement over the situation just a few years ago, but we are hindered by our assumptions.
    - Limiting magnitude
    - Escape fraction



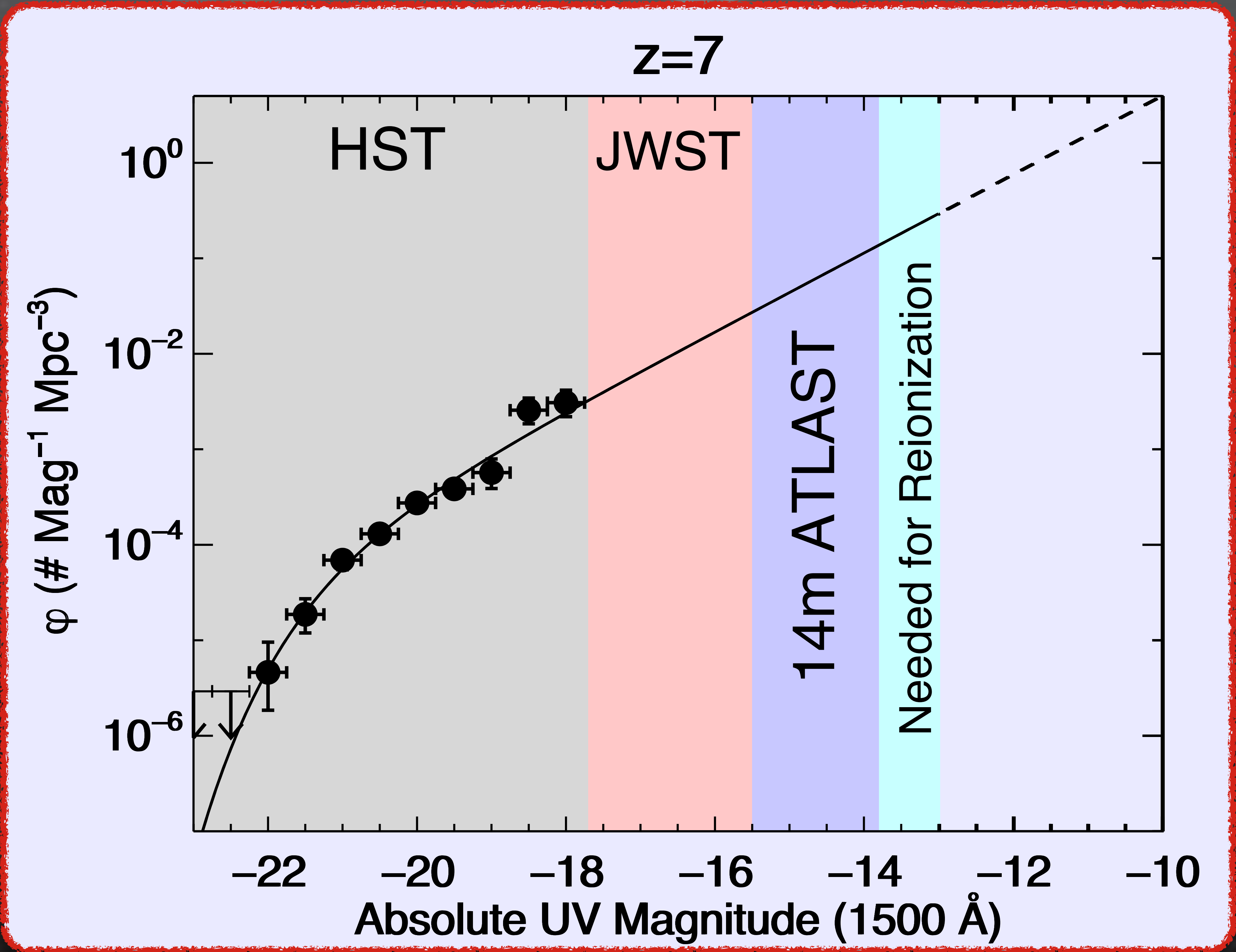
LIMITING MAGNITUDE

- It is expected that the ionizing background will suppress SF in halos below M ~ -10, but recent studies have found that the UV LF may turn at brighter magnitudes (Jaacks+13, O'Shea+15, Boylan-Kolchin+15).
  - We need to understand the luminosity function down to -13. If it turns over at brighter magnitudes, we have a photon production crisis.
- How can we test this?
  - 1) Lensing - The Hubble Frontier Fields
    - Drawbacks: small volumes, uncertain magnification corrections.
  - 2) JWST: deep fields will reach around -15.5 in UV absolute magnitude.
    - Still not deep enough, though with lensing it will certainy go past -13 (with the same caveats as the HFF)
- 3) ATLAST/HDST 12-14m UVOIR space telescope.



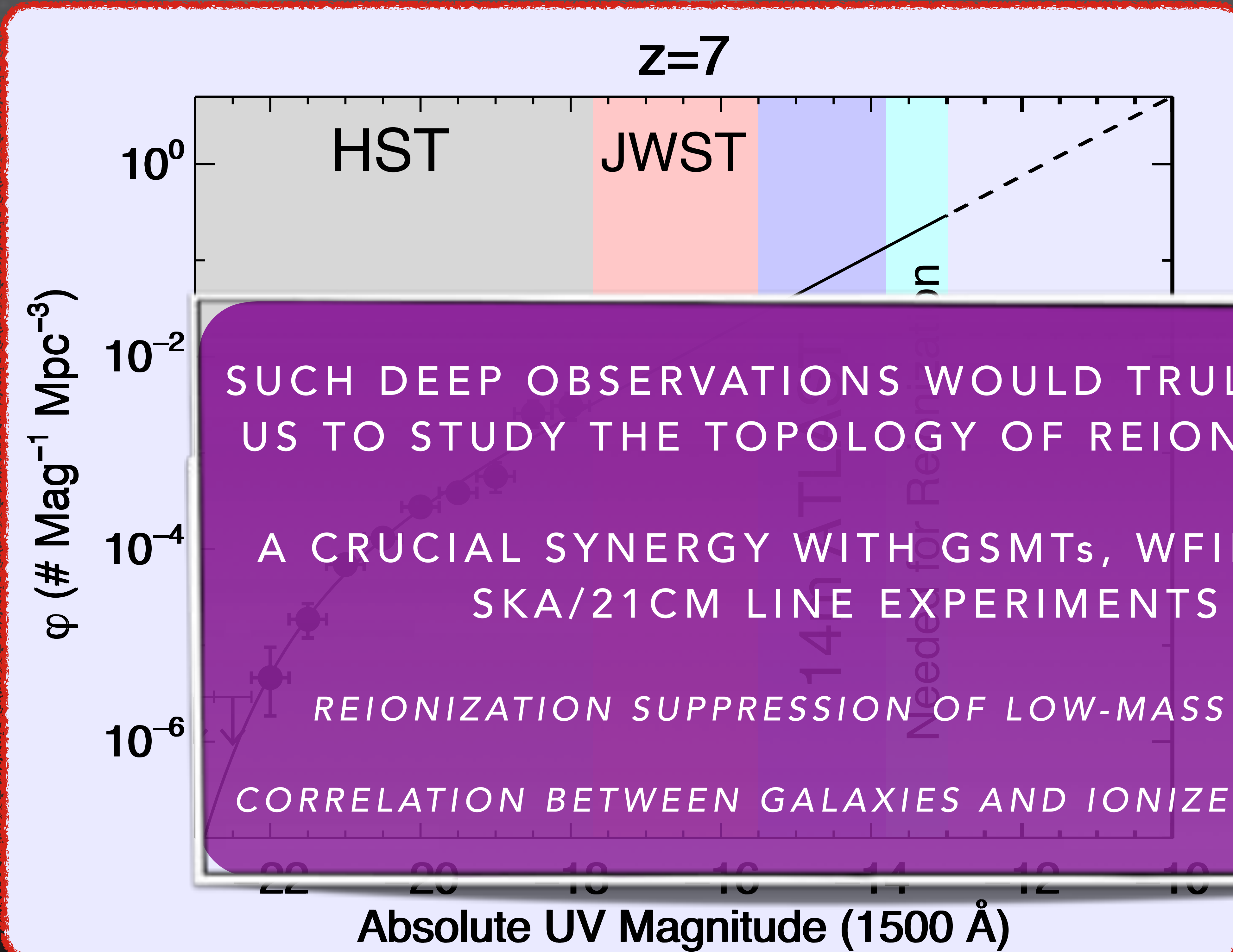
LIVERMORE, SF & LOTZ 2016

ACCOUNTING FOR ALL REIONIZING PHOTONS WITH ATLAST



TELESCOPE	FRACTION OF REIONIZING PHOTONS ACCOUNTED
HST	35%
JWST	60%
ATLAST (14M)	90%

ACCOUNTING FOR ALL REIONIZING PHOTONS WITH ATLAST



SUCH DEEP OBSERVATIONS WOULD TRULY ALLOW US TO STUDY THE TOPOLOGY OF REIONIZATION

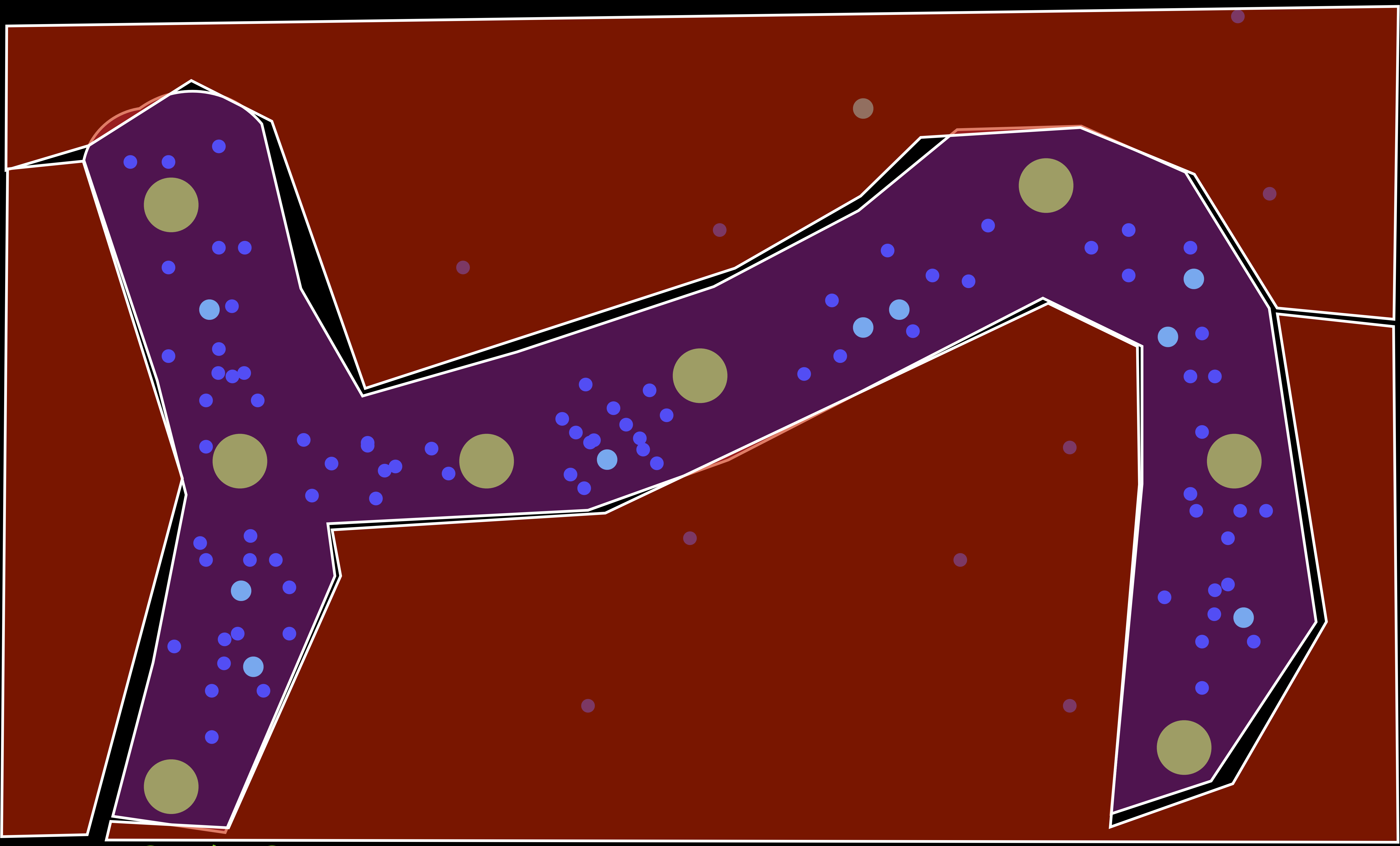
A CRUCIAL SYNERGY WITH GSMTs, WFIRST, and SKA/21CM LINE EXPERIMENTS

REIONIZATION SUPPRESSION OF LOW-MASS HALOS

CORRELATION BETWEEN GALAXIES AND IONIZED PATCHES

	FRACTION OF REIONIZING PHOTONS ACCOUNTED
HST	35%
JWST	60%
ATLAST (14M)	90%

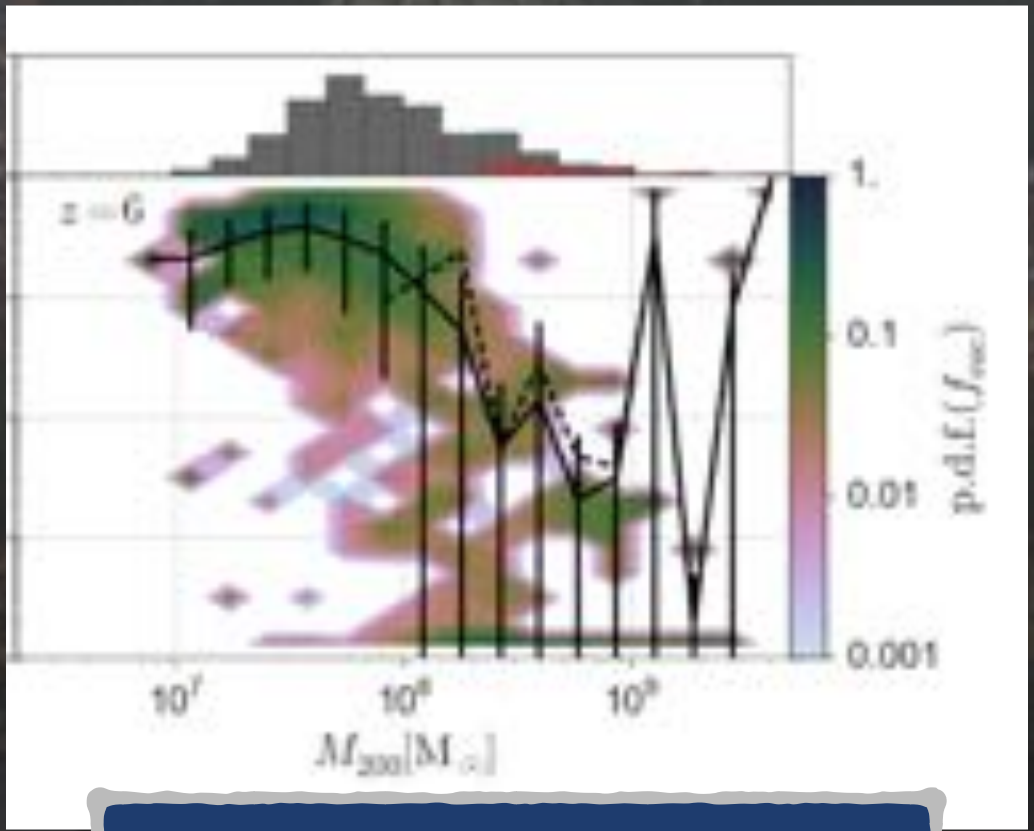
FANCY ANIMATION



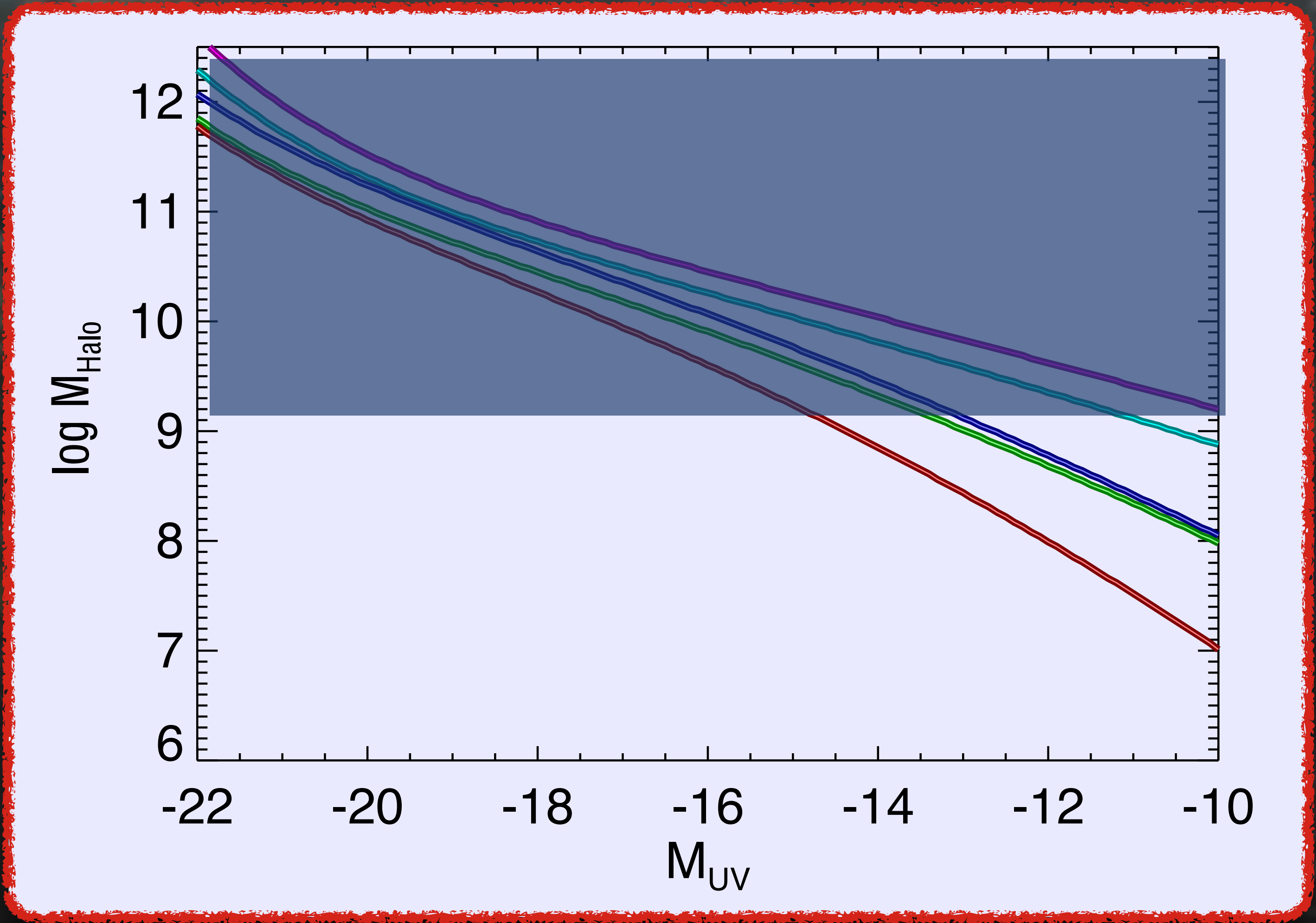
WFIRST/HST JWST ATLAST/HDST GMT SKA

ESCAPE FRACTION

- The other main assumption was the escape fraction of ionizing photons.
    - The analysis showed today assumed 13%.
    - Nearly *all* observations at z < 4 result in non-detections, with typical limits on f_{esc} of less than a few percent (Siana+10), though there are isolated cases of some galaxies have f_{esc} ~20-30% (Nestor+11).
    - Most simulations show very low escape fractions in the galaxies we see, and imply that only very low-mass halos have conditions which promote ionizing photon escape.



PAARDEKOOPER+15



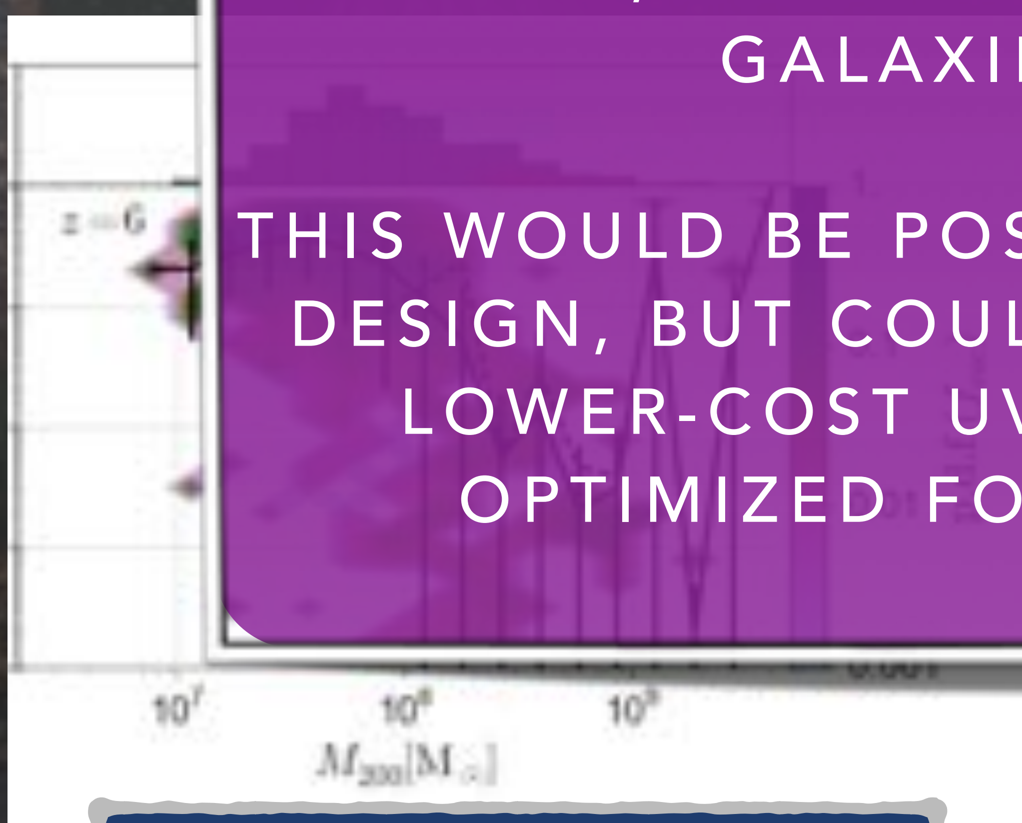
ESCAPE FRACTION

- The other main assumption was the escape fraction of ionizing photons.
    - The analysis showed today assumed 13%.
    - Ne… an a few pe… or+11).
    - Most simulations show very low escape fractions in the galaxies we see, and imply that only very low-mass halos have conditions which promote ionizing photon escape.

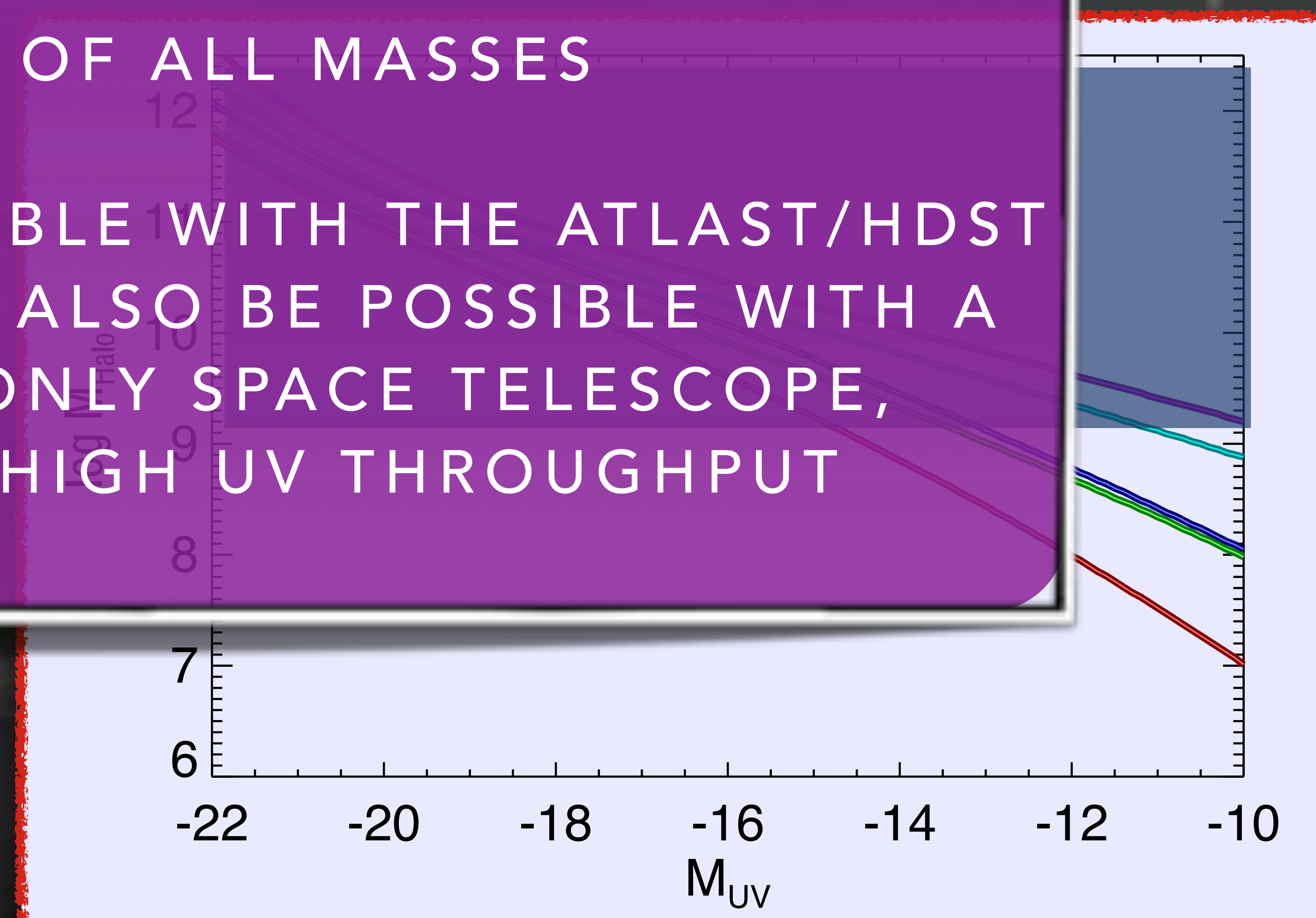
THIS COULD ALSO CREATE A PHOTON "CRISIS"

WE NEED TO MEASURE, EVEN AT LOWER REDSHIFT, WHAT THE ESCAPE FRACTION IS FROM GALAXIES OF ALL MASSES

THIS WOULD BE POSSIBLE WITH THE ATLAST/HDST DESIGN, BUT COULD ALSO BE POSSIBLE WITH A LOWER-COST UV-ONLY SPACE TELESCOPE, OPTIMIZED FOR HIGH UV THROUGHPUT



PAARDEKOOPER+15



TAKE AWAY POINTS

- Progress has been excellent (see agreement on luminosity functions!) but there are a lot of unknowns about the high-redshift universe.
    - We will learn much with JWST and WFIRST, but many of our assumptions which underlie our conclusions on reionization will not be justified.
        - A very large aperture space telescope will allow us to directly observe the galaxies responsible for reionization, while a lower cost UV-optimized facility can allow us to directly probe ionizing photons.